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Origins Space Telescope science drivers to design traceability

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Abstract. The Origins Space Telescope (Origins) concept is designed to investigate the creation and dispersal of elements essential to life, the formation of planetary systems, and the transport of water to habitable worlds and the atmospheres of exoplanets around nearby K- and M-dwarfs to identify potentially habitable—and even inhabited—worlds. These science priorities are aligned with NASA's three major astrophysics science goals: How does the Universe work? How did we get here? and Are we alone? We briefly describe the science case that arose from the astronomical community and the science traceability matrix for Origins. The science traceability matrix prescribes the design of Origins and demonstrates that it will address the key science questions motivated by the science case. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JATIS.7.1.011012](https://doi.org/10.1117/1.JATIS.7.1.011012)]

Keywords: infrared; cryogenic space telescope; spectroscopy; galaxy evolution; planet formation; biosignatures.

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1 Introduction

The Origins Space Telescope (Origins) traces our cosmic history, from the formation of the first galaxies and the rise of metals to the development of habitable worlds and present-day life. Origins does this through exquisite sensitivity to infrared radiation from ions, atoms, molecules, dust, water vapor, and ice, and observations of extrasolar planetary atmospheres, protoplanetary disks, and large-area extragalactic fields. Origins operates in the wavelength range 2.8 to 588 μm and is >1000 times more sensitive than its predecessors due to its large (5.9 m/25 m²), cold (4.5 K) telescope, and advanced instruments.¹

The science case for Origins was derived from the astronomical community through an extensive three-year exercise led by the Origins science working groups on galaxy evolution and cosmology, the Milky Way and nearby galaxies, planetary system formation, and exoplanets. The science input was prioritized and organized into three science themes that align with NASA's Astrophysics three thematic questions (Table 1). Each science theme has three science objectives that are specific questions that Origins will address. These science objectives specify the science requirements for the Origins design that are captured in the science traceability matrix (STM; Fig. 1).

In this paper, we briefly describe the science case and traceability matrix for Origins. The full science case is described in the Origins Space Telescope Study report.^{2,3} The science case builds upon expected advances from, and limitations of, current and next-generation observatories, namely, James Webb Space Telescope (JWST),⁴ Nancy Grace Roman Space Telescope,⁵ Atacama Large Millimeter Array (ALMA),⁶ and Vera C. Rubin Observatory.⁷ Origins addresses the key science goals by achieving its nine scientific objectives in 2 years. Thus, Origins will enable astronomers in the 2030s to ask new questions not yet imagined and provide a far-infrared window complementary to planned, next-generation observatories, such as the Laser Interferometer Space Antenna (LISA),⁸ Advanced LIGO,⁹ Athena,¹⁰ the Square Kilometer Array,¹¹ and ground-based Extremely Large Telescopes (ELTs).¹²

The remainder of this paper is organized as follows. Section 2 describes the extragalactic case, which was coled by Alexandra Pope and Lee Armus. Section 3 highlights the planetary system formation case, which was coled by Klaus Pontoppidan, Edwin Bergin, and Kate Su.

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Table 1 Mission design scientific drivers for the Origins Space Telescope.

| NASA goal | How does the universe work? | How did we get here? | Are we alone? |
|---------------------------------|---|--|--|
| Origins science goals | How do galaxies form stars, make metals, and grow their central SMBHs from reionization to today? | How do the conditions for habitability develop during the process of planet formation? | Do planets orbiting M-dwarf stars support life? |
| Origins scientific capabilities | With spectroscopic maps of wide extragalactic fields, Origins will simultaneously measure properties of growing SMBHs and their galaxy hosts across cosmic time. | With sensitive, high-resolution far-IR spectroscopy, Origins maps the water trail from protoplanetary disks to habitable worlds. | With precise mid-infrared transmission and emission spectra, Origins will assess the habitability of nearby exoplanets and search for signs of life. |
| Origins scientific objectives | (1) How does the relative growth of stars and SMBHs in galaxies evolve with time? (2) How do galaxies make metals, dust, and organic molecules? (3) How do the relative energetics from supernovae and quasars influence the interstellar medium of galaxies? | (1) What role does water play in the formation and evolution of habitable planets? (2) How and when do planets form? (3) How were water and life's ingredients delivered to Earth and to exoplanets? | (1) What fraction of terrestrial planets around M- and K-dwarf stars has tenuous, clear, or cloudy atmospheres? (2) What fraction of terrestrial M-dwarf planets is temperate? (3) What types of temperate, terrestrial, M-dwarf planets support life? |

Section 4 provides an overview of the exoplanet case, which was coled by Kevin Stevenson, Tiffany Kataria, and Jonathan Fortney. Section 5 discusses the full Origins STM defined by the three themes and one imaging polarization case identified by the Milky Way and nearby galaxy science working group, which was coled by Cara Battersby and Karin Sandstrom. Section 6 discusses the discovery space for Origins.

2 Extragalactic Case

Origins will address the following key question about galaxy evolution: How do galaxies form stars, make metals, and grow their central supermassive black holes (SMBHs), from the Epoch of Reionization to today?

Decades of observations have shown that galaxies condensed out of primordial gas, built up their stellar mass, heavy metals, and central supermassive black holes (SMBHs), and evolved into the systems we see today. Yet we still do not understand how this happened. There is a rich interplay between the drivers of galaxy evolution, which can only be understood through new observations in a currently inaccessible wavelength regime, the far-infrared (Fig. 2).

Far-infrared observations are required because galaxies are dusty. Dust is a byproduct of star formation and is essential to astrophysical processes, from planetesimal formation in protoplanetary disks, to radiation-driven galactic outflows.¹⁴ Dust also obscures star formation and SMBH growth since it efficiently absorbs ultraviolet and optical light, rendering the driving processes of galaxy evolution nearly invisible at these wavelengths. However, the dust re-emits this energy in the far-infrared, making optically dim galaxies brilliant infrared sources. Just as importantly, infrared and molecular emission lines, which directly trace star formation, black-hole growth, and metal abundances, can escape dusty galaxies, making the mid- and far-infrared the only bands where a direct, unbiased view of the galaxy and metal growth is possible.¹⁵ This lesson was reinforced by Spitzer¹⁶ and Herschel,¹⁷ which provided our first census of dusty galaxies in the infrared during the peak epoch of star formation, when the Universe was only 3 Gyr old.¹⁸ With 1000 times the sensitivity, Origins gives us a clear view of galaxy and metal growth across cosmic time, through a deep-and-wide

| Table 2: Origins Science Traceability Matrix | | | | | | | | | |
|--|---|--|--|--|---|--|-----------------------|---|---|
| NASA Science Goals | Origins Science Goal/Question | Science Objectives | Science Requirements | | Instrument Requirements | | | Mission Requirements | |
| | | | Science Observable | Measurement Requirement | Parameter | Technical Requirement | Inst ^r | CBE Performance | Driver |
| How does the Universe work? | How do galaxies form stars, build up metals, and grow their central black holes from reionization to today? | Objective #1 and #2: Measure the redshifts, star formation rates and black hole accretion rates in main-sequence galaxies since the epoch of reionization, down to a SFR of $1 M_{\odot}/\text{yr}$ at cosmic noon and $10 M_{\odot}/\text{yr}$ at $z=5$, performing the first unbiased survey of the co-evolution of stars and supermassive black holes over cosmic time. Measure the metal and dust content of at least 10^5 galaxies out to $z=6$ as a function of cosmic time, morphology, and environment, tracing the rise of heavy elements, dust and organic molecules. | A catalog of 10^6 galaxies with star-formation rates and the black hole accretion rates measured using mid and far-IR emission lines. Multi-tiered survey leveraging a deep $1 \text{ deg}^2 \times 2 \text{ } \mu\text{m}$ imaging from JWST/NIRCAM, a $\sim 500 \text{ deg}^2$ medium depth survey for large-scale structure overlapping with WFIRST-HLS, and map the full $10,000 \text{ deg}^2$ for comparison with LSST and Euclid. | Moderate ($R \geq 100$) spectral resolution survey spanning 0.5 deg^2 and 20 deg^2 to deep and shallow depths, respectively. | Wavelength range Spectral resolving power $R = \lambda/\Delta \lambda$ Angular resolution Number of beams (beams capture field-of-view) Spectral line sensitivity | 25–500 μm ≥ 100 $\leq 8''$ at $100 \text{ } \mu\text{m}$ 50 at $100 \text{ } \mu\text{m}$ $1.5 \times 10^{-20} \text{ W m}^{-2}$ at $250 \text{ } \mu\text{m}$ (1 hr, 5 σ) | OSS-grating | 25–588 μm 300 4.3'' at $100 \text{ } \mu\text{m}$ 60 at $100 \text{ } \mu\text{m}$; 96 at $25 \text{ } \mu\text{m}$; 36 at $500 \text{ } \mu\text{m}$ | To meet Objectives #1–#3 in a 4000 hr observing campaign, telescope aperture with diam-eter $> 5.0 \text{ m}$. Source count requires a diameter $> 3.0 \text{ m}$. To meet Objectives #1–#3, a cold aperture with a temperature $< 6 \text{ K}$. Down to a line flux sensitivity of $10^{-19} \text{ W m}^{-2}$ ability to map better than $0.15 \text{ deg}^2/\text{hr}$ and efficient scan mapping at a rate as high as 60 arcsec/sec . To enable access to all targets of interest, the field of regard shall be 4π over the course of the mission. To enable object matching with near-IR counterparts, the pointing accuracy after ground processing shall be $\leq 0.5 \text{ arcsec}$ at $50 \text{ } \mu\text{m}$. To enable survey sciences, FIP and OSS must allow parallel observations. The spacecraft shall enable a data transmission of 21 This day (99% of data collected) day with FIP and OSS surveys in parallel. |
| | | | | | | | | | |
| | | | | | Polarization sensitivity | 1% (3 σ) in linear and circular polarization | FIP-continuum mapping | 0.1% (3 σ), 1 degree in pol angle | Point source sensitivity, stability and systematic error control |
| | | | | | Wavelength range Spectral resolving power $R = \lambda/\Delta \lambda$ | 35 – 476 μm ≥ 3000 over the wavelength range | OSS-FTS | 25–588 μm 43,000 \times (112 $\mu\text{m}/\lambda$) as provided by FTS element | |
| | | | | | Angular resolution | $\leq 8''$ at $100 \text{ } \mu\text{m}$ to avoid source confusion at $\lambda < 100 \text{ } \mu\text{m}$ (1 hr, 5 σ) | | 4.3'' | |
| | | | | | Spectral line sensitivity | $2 \times 10^{-20} \text{ W m}^{-2}$ at $119 \text{ } \mu\text{m}$ (1 hr, 5 σ) | | 8 $\times 10^{-21} \text{ W m}^{-2}$ at $119 \text{ } \mu\text{m}$ (1 hr, 5 σ) | |

| Table 2 cont.: <i>Origins Science Traceability Matrix</i> | | | | | | | | | | | | |
|---|--|--|--|--|---|---|-------------------|--|---|--|--|--|
| NASA Science Goals | Origins Science Goal/Question | Science Objectives | Science Requirements | | Instrument Requirements | | | Mission Requirements | | | | |
| | | | Science Observable | Measurement Requirement | Parameter | Technical Requirement | Inst ^r | CBE Performance | Driver | | | |
| How did we get here? | How do the conditions for habitability develop during the process of planet formation? | Objective #1: Measure the water mass at all evolutionary stages of star and planet formation and across the range of stellar masses, tracing level energies between 114 K and 5000 K in the spectral range 25 to 548 μ m (longest is H ₂ O 1–1 at 547.4 μ m). | H ₂ O 2 _v –1 _v 179.5- μ m line emission in protoplanetary disks. Also, representative H ₂ O lines with upper level energies between 114 K and 5000 K in the spectral range 25 to 548 μ m (longest is H ₂ O 1–1 at 547.4 μ m). | Detect 179.5 μ m and other representative H ₂ O emission lines out to 547.7 μ m in a 0.7 x MMSN disk around a 0.25 solar mass star at the distance of Orion. | Wavelength range Angular resolution Spectral line sensitivity Spectral resolving power $R = \lambda/\Delta \lambda$ | 25 to 548 μ m $\leq 15''$ to avoid source confusion at Orion 1×10^{-20} W m ² at 179.5 μ m (1 hr, 5 σ) 25,000 at 179.5 μ m | OSS-FTS | 25 to 588 μ m 77 FWHM at 179.5 μ m 7×10^{-21} W m ² (1 hr, 5 σ) 27,000 at 179.5 μ m | Point source sensitivity, stability and systematic error control | | | |
| | | | Spectrally resolve H ₂ O 179.5 μ m emission line enabling Doppler tomographic measurements, with continuum sensitivity for sources ≤ 10 Jy at 179.5 μ m. | Wavelength range Continuum Saturation limit Spectral resolving power $R = \lambda/\Delta \lambda$ | 179.5 +/- 10 μ m 10 Jy at 179.5 μ m 200,000 at 179.5 μ m | | OSS-etalon | 100 to 200 μ m 100 Jy at 179.5 μ m 202,785 at 179.5 μ m | | | | |
| | | Objective #2: Determine the ability of planet-forming disks at all evolutionary stages and around stars of all masses to form planets with masses as low as one Neptune using the HD 1–0 line to measure the total disk gas mass. | Use the HD 1–0 line at 112 μ m as a tracer of total gas mass. | Detect HD J=1–0 line emission at 112 μ m in a 0.7 x MMSN disk around a solar mass star at $d = 125$ pc. Ability to study disks ≤ 10 Jy at 100 μ m. | Wavelength range Spectral line sensitivity Spectral resolving power $R = \lambda/\Delta \lambda$ | 112 +/- 10 μ m 1×10^{-20} W m ² at 112 μ m (1 hr, 5 σ) 40,000 at 112 μ m | | OSS-FTS | Same as above Same as above 43,000 at 112 μ m | To enable access to all targets of interest, the field of regard shall be 4 π sr over the course of the mission. | | |
| | | | DIH ratio in water via observations of the water (H ₂ O) and deuterated water (HDO) emission lines from periodic and Oort cloud comets. | Detect water H ₂ O (243.7, 273.2 μ m), H ₂ ¹⁸ O (272.1 μ m), and deuterated water HDO (234.6 μ m) line emission, in a typical comet. Ability to study DIH ratios for comets ≤ 3 Jy at 234.6 μ m. | Wavelength range Angular resolution Continuum Saturation limit Spectral resolving power $R = \lambda/\Delta \lambda$ | 230 - 275 μ m $\leq 16''$ at 234.6 μ m 3 Jy at 128 μ m $\geq 10,000$ | | OSS-FTS | Same as above 10 arcsec at 234.6 μ m 5 Jy at 128 μ m 37,000 at 128 μ m | | | |
| Table 2 cont.: <i>Origins Science Traceability Matrix</i> | | | | | | | | | | | | |
| Science Requirements | | | Instrument Requirements | | | Mission Requirements | | | | | | |
| Science Requirements | | | Instrument Requirements | | | Mission Requirements | | | | | | |

Fig. 1 (Continued)

| NASA Science Goals | Origins Science Goal/Question | Science Objectives | Science Observable | Measurement Requirement | Parameter | Technical Requirement | Instr | CBE Performance | Driver | Parameter |
|--------------------|---|--|---|---|--|---|---------------------------|---|--|--|
| Are We Alone? | Do planets orbiting M-dwarf stars support life? | Objective #1: Distinguish between tenuous, clear, and cloudy atmospheres on at least 28 temperate, terrestrial planets orbiting M and K dwarfs using CO and other spectral features. | Transmission spectra sensitive to CO ₂ (4.2 μ m), H ₂ O (6.3 μ m), O ₃ (9.7 μ m), and CH ₄ (3.3 μ m). | Simultaneous 3.0–10.5 μ m transmission spectra with an average of eight 4-hour transits to achieve $\geq 3.6\sigma$ detection of spectral features, for stars with $K_{mag} \geq 4$ to 11.5 | Wavelength range Spectral resolving power $R = \lambda/\Delta\lambda$ Sensitivity Saturation/Brightness Limit | 3–10.5 μ m simultaneous 50–100 K–9.85 mag M-type star SNR/sqrt(hr) > 10,000 at 3.3 μ m K = 4.0 mag star | MISC-Transit Spectrometer | 2.85–20.5 μ m 50–100 K–9.85 mag M-type star SNR/sqrt(hr) > 12,900 at 3.3 μ m K=2.9 mag star Or 30 Jy at 3.3 μ m | Point source sensitivity, stability and systematic error control | • Pointing jitter and drift shall not compromise the ability of MISC-T to make transit/eclipse spectroscopy measurements. From spacecraft attitude control, jitter must be ≤ 50 mas (rms) at $\lambda > 1$ Hz, and the drift must be ≤ 50 mas (rms) over 1–10 hours. • Including the MISC-T feedback to the field steering mirror, jitter must be ≤ 10 mas (rms) over 1–10 hours. • Spatial Resolution provided by an equivalent field-stop radius $\leq 2.5''$ at 2.8–10.5 μ m and $\leq 1.5''$ at 10.5–20 μ m • To meet objectives #1–#3 in a total of 4000 hour observing campaign, a telescope collecting area of 22.6 m ² (5.3 m diameter) • To enable access to all targets of interest, the field of regard shall be 4 π sr over the course of the mission. |
| | | Objective #2: Establish the apparent surface temperatures of at least 17 terrestrial exoplanets with the clearest atmospheres and distinguish between boiling and freezing surface water at $\geq 3\sigma$ confidence (± 33 K). | Emission spectra with sufficient time resolution to resolve ingress and egress. | Simultaneous 4.0–20 μ m emission spectra with an average of 15 4-hour eclipses to achieve 33 K 1 σ precision on the apparent surface temperatures. | Wavelength range Spectral resolving power $R = \lambda/\Delta\lambda$ Spectroscopic precision | 11–20 μ m simultaneous $R > 250$ at $\lambda > 17$ μ m ≤ 20 ppm at 15 μ m ($R = 100$) ≤ 60.0 sec for K = 11.5 mag star | | Same as above 260–295 over 17–20.5 μ m ≤ 15 ppm at 15 μ m ($R = 100$) Sensitivity and precision above | | |
| | | Objective #3: Search for biosignatures on at least 10 planets, highest ranked from Objectives 1 and 2, and if present, detect biosignatures at $\geq 3.6\sigma$ (assuming an Earth-like atmosphere) | Transmission spectra sensitive to CH ₄ , N ₂ O, and O ₃ . | Simultaneous 3.0–20 μ m transmission spectra with an average of 52 4-hour transits to achieve $\geq 3.6\sigma$ detections of biosignatures (if present). | Wavelength range Spectral resolving power $R = \lambda/\Delta\lambda$ Spectroscopic precision | 3.0–20 μ m simultaneous Same as above ≤ 5 ppm at $\lambda = 3$ –10.5 μ m ($R = 50$); ≤ 20 ppm at $\lambda = 10.5$ –20 μ m ($R = 100$) | | Same as above Same as above | | |
| | | | | | Spectral line sensitivity | ≥ 125 days of visibility per year for any given target | | ≤ 5 ppm at 10 μ m ($R = 50$); ≤ 20 ppm at 20 μ m ($R = 100$) 130 days of visibility at treecopic; more at higher latitudes | | |

Fig. 1 (Continued)

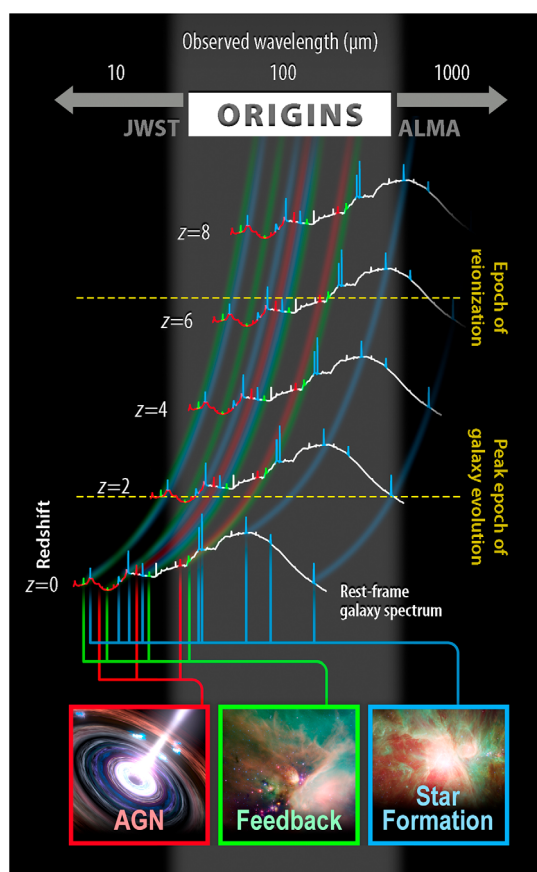


Fig. 2 Spectral reach of Origins over cosmic time showing a schematic representation of how the key spectral diagnostic features of active galactic nuclei (AGN, red), star formation (blue), and energetic feedback (green) move through the wide bandpass of the OSS¹³ with look-back time. Origins can measure all of these important processes over the entire history of galaxy evolution, filling in a key gap in wavelength and discovery space between JWST and ALMA.

spectroscopic survey in a wavelength regime inaccessible from the ground and that will remain unexplored by JWST.¹⁵

The over-arching extragalactic science goal is specifically addressed by three questions described below that correspond to science measurements in the traceability matrix.

2.1 *How Do the Stars and Supermassive Black Holes in Galaxies Evolve with Time?*

Origins uses atomic and molecular emission lines and emission from dust grains to measure the density, temperature, and ionization state of the gas where stars are forming and in galactic nuclei.¹⁵ These observations probe the physics of the interstellar medium, characterize the atomic and molecular gas that drives star-formation, measure the buildup of metals from dying stars, and track the growth of SMBHs and their influence, as they drive energetic outflows into the surrounding interstellar medium (Fig. 3).

2.2 *How Do Galaxies Make Metals, Dust, and Organic Molecules?*

Galaxies are the metal factories of the Universe, and Origins studies how heavy elements and dust were made and dispersed throughout the cosmic web over the past 12 billion years.¹⁹ Sensitive metallicity indicators in the infrared can be used to track the growth of heavy elements in even the densest optically obscured regions inside galaxies.

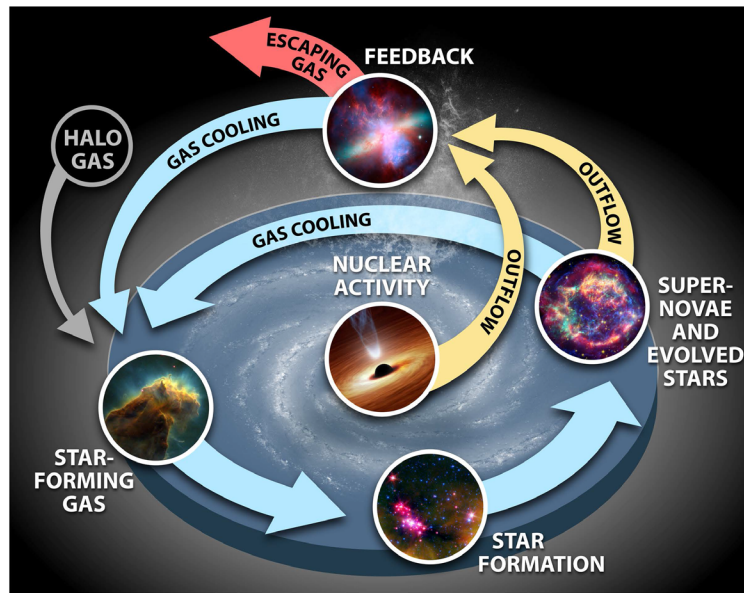


Fig. 3 Origins studies the baryon cycle in galactic ecosystems. Energetic processes that shape galaxies and the circumgalactic medium together define this ecosystem. Through its ability to measure the energetics and dynamics of the atomic and molecular gas and dust in and around galaxies, Origins can probe nearly all aspects of the galactic ecosystem: star formation and AGN growth; stellar death; AGN- and starburst-driven outflows; and gas cooling and accretion. These measurements provide a complete picture of the lifecycle of galaxies.

2.3 How Do the Relative Energetics from Supernovae and Quasars Influence the Interstellar Medium of Galaxies?

Galaxies are made of billions of stars, yet star formation is extremely inefficient on all scales, from single molecular clouds to galaxy clusters. The reason is thought to be “feedback” from star formation or black hole growth, because supernovae or quasar winds can disrupt star-forming gas.²⁰ Origins studies the role of feedback processes in galaxies over a wide range of environments and redshifts by investigating the processes that drive powerful outflows and by surveying the demographics of galactic feedback.

3 Planetary System Formation Case

Origins will address the following key question about the formation and evolution of planetary systems (Fig. 4): How do the conditions for habitability develop during the process of planet formation?

Water is essential to all life on our planet. Water provides the liquid medium for life’s chemistry and plays an essential biochemical role. However, we do not know how terrestrial planets get their liquid water. Rocky planets with liquid water exist in regions of the protoplanetary disk where water was not available during the planetary system formation because the star would have sublimated and photodissociated the water ice off the protoplanetary dust at this location. With its broad wavelength coverage, Origins can detect many water vapor lines that trace the entire range of temperatures found in protoplanetary disks, from the cold snowline to the hot steam line in disks (Fig. 5).²¹ Origins can survey all reservoirs of water in more than 1000 planet-forming disks around stars of all masses, including the faint M-dwarfs that likely host most planets in the Galaxy.

Another puzzle in planetary formation is the role of hydrogen gas in protoplanetary disks. The disk’s gas reservoir is essential to form gas giants. Moreover, the coupling of the gas to the dust may affect the formation and composition of planetesimals, which are the building blocks of

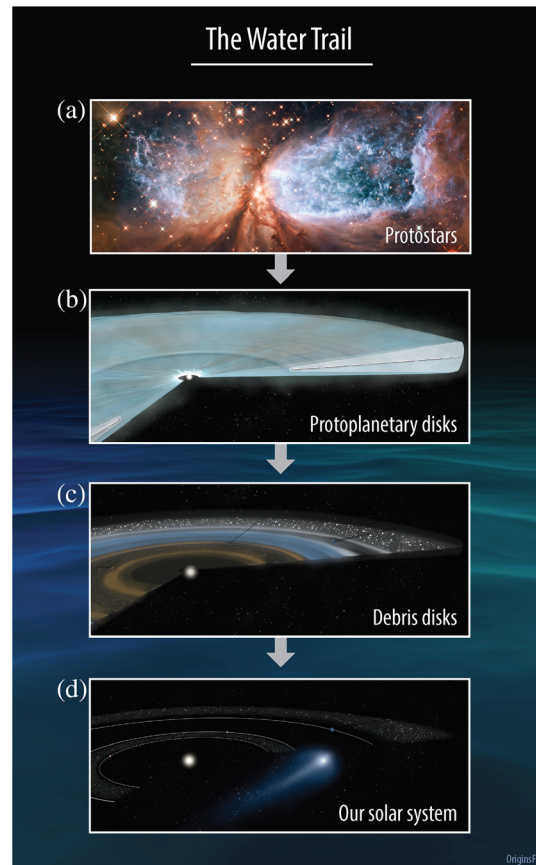


Fig. 4 Origins will trace water and gas during all phases of the formation of a planetary system. The trail begins in the “prestellar” phase explored by Herschel, where (a) a cloud of gas collapses into a still-forming star surrounded by a disk nearly the size of our solar system and (b) a collapsing envelope of material. Over time, (c) the envelope dissipates, leaving behind a young star and a disk with nascent planets, (d) eventually leaving behind a new planetary system. Origins will excel at probing the protoplanetary and later phases.

rocky planets. Despite decades of effort, the hydrogen gas mass of protoplanetary disks is essentially unknown because molecular hydrogen (H_2), being a symmetric molecule, requires significant energy to excite its rotational levels. Hence, molecular hydrogen is largely invisible at the low temperatures of planet-forming gas. Carbon monoxide (CO), which is the second most abundant molecule to H_2 , has been a traditional tracer for H_2 in the interstellar medium. However, in protoplanetary disks CO -estimated H_2 masses are uncertain by factors of 10 to 100 in disks because the physical conditions in disks is very different than the interstellar medium. Origins can observe the $\text{HD } 112 \mu\text{m}$ line, which provides a new and robust measure of disk gas mass.²²

The planetary system formation science goal is specifically addressed by three questions described below that correspond to science measurements in the traceability matrix.

3.1 What Role Does Water Play in the Formation and Evolution of Habitable Planets?

With its unprecedented sensitivity to weak emission from all forms of water (ice as well as gas), Origins deciphers the role of water throughout each phase of planetary system formation (Figs. 4 and 5).²¹ The Origins wavelength range includes warm water lines between 25 and 100 μm , and the ground-state lines at 179.5 and 538 μm . Origins observers will use these tracers to quantify the gas mass and the location of water in planet-forming disks. The model protoplanetary disk

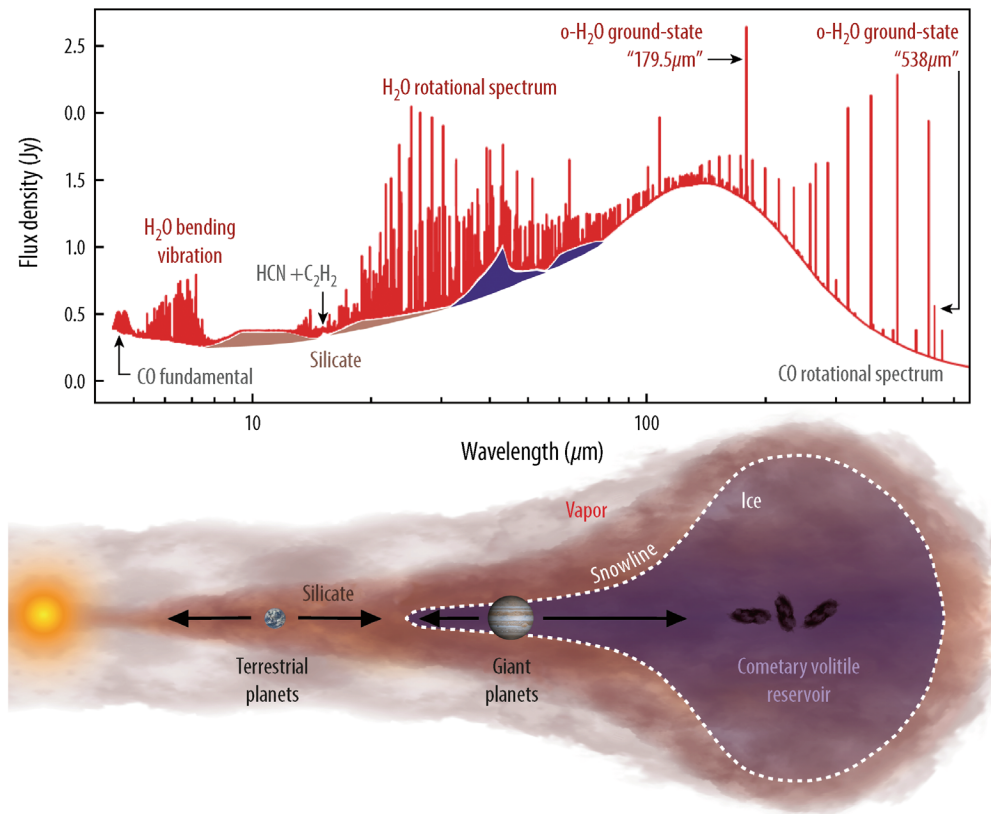


Fig. 5 Origins provides access to critical molecular tracers, including the HD $J = 1-0$ line at $112 \mu\text{m}$, and nearly the full H_2O rotational spectrum. Also shown is a schematic of the different water regions in a planet-forming disk. The main regions include inner disk warm water vapor, midplane ice, and outer disk cold (photoevaporated) water vapor. Origins will probe the water and gas mass content throughout the disk.

spectrum in Fig. 5 is rendered at 4 to $660 \mu\text{m}$ with a uniform 6 km s^{-1} spectral resolving power and for a disk distance of 125 pc. Previous spectroscopic observations of disks with Spitzer and Herschel were under-resolved, and therefore, did not show the dramatic line-to-continuum ratios to be revealed by Origins. JWST is only sensitive to warm, highly excited water lines near the star but not the cold-gas water lines that arise throughout the protoplanetary disk and serve as the best tracers of water during planetary system formation. Indeed, Origins accessibility to the cold water lines is very complementary to measurements made by JWST and ALMA, which are not as sensitive to water lines (Fig. 6).

3.2 How and When Do Planets Form?

Origins can uniquely use the HD $112 \mu\text{m}$ emission line, which is a powerful tool to measure the gas mass of protoplanetary disks to within a factor of 2 to 3.²² This precision is one to two orders of magnitude better than alternative tracers and can distinguish between competing models of planet formation and set the timescale for gas-giant formation. Origins' gas-mass measurements have the potential to provide calibrations for all other observations of protoplanetary disks, including those made with ALMA using CO isotopes.

3.3 How Were Water and Life's Ingredients Delivered to Earth and to Exoplanets?

Earth likely formed within the snowline: the distance from a young star where water transitions from a gas to a solid. Thus, water was not a solid in the planetesimals where Earth formed. The

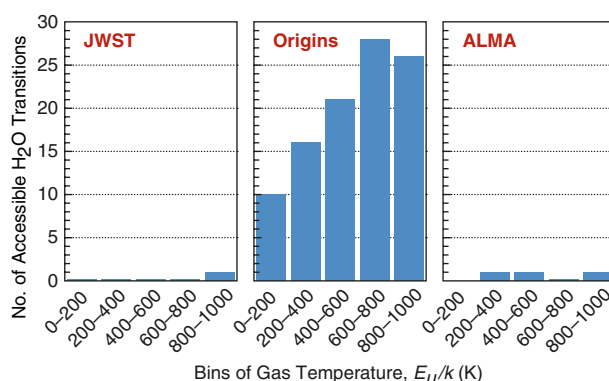


Fig. 6 Origins studies more than 100 transitions of the relevant water vapor lines, compared with one and three with JWST and ALMA, respectively. The plot shows the number of H₂O transitions observable by JWST, Origins, and ALMA as a function of the gas temperature for energies above the ground state but less than 1000 K gas temperature. Gas temperatures less than 1000 K are the most relevant for studies of water throughout the protoplanetary disk and the formation of planetary systems. JWST probes only warm water lines close to the star. ALMA is limited by atmospheric absorption in its ability to observe water.

prevailing theory holds that water was delivered to the early Earth via impacts by bodies that formed beyond the snowline. The evidence for this comes from the relatively high deuterium content of Earth's oceans relative to the protosolar nebula, an excess that is locked when water is formed at a temperature of 10 to 20 K.²³ In our Solar System, comets and asteroids also carry this signature. Only a handful of comets have been measured to date and they show a range of deuterium abundances. With a larger sample of comets, Origins can finally establish the relative contributions of comets versus asteroids to the source of Earth's water.

4 Exoplanets

Origins will address the following key question about exoplanets: Do planets orbiting M-dwarf stars support life?

Humankind has long pondered the question, “Are we alone?” Our quest to search for life on planets around other stars relies on our ability to measure the chemical composition of their atmospheres and understand the data in the context of models for planet formation and evolution (Fig. 7). Using the techniques of transmission and emission spectroscopy, Origins will expand

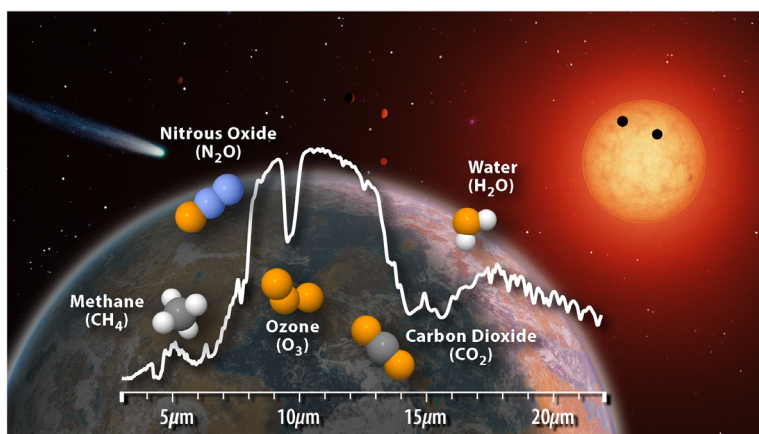


Fig. 7 Origins is designed to characterize already-discovered rocky planets that transit M dwarf stars and place critical constraints on their temperatures. By leveraging the midinfrared wavelengths offered by Origins, these atmospheres can be examined for gases that are the most important signatures of life.

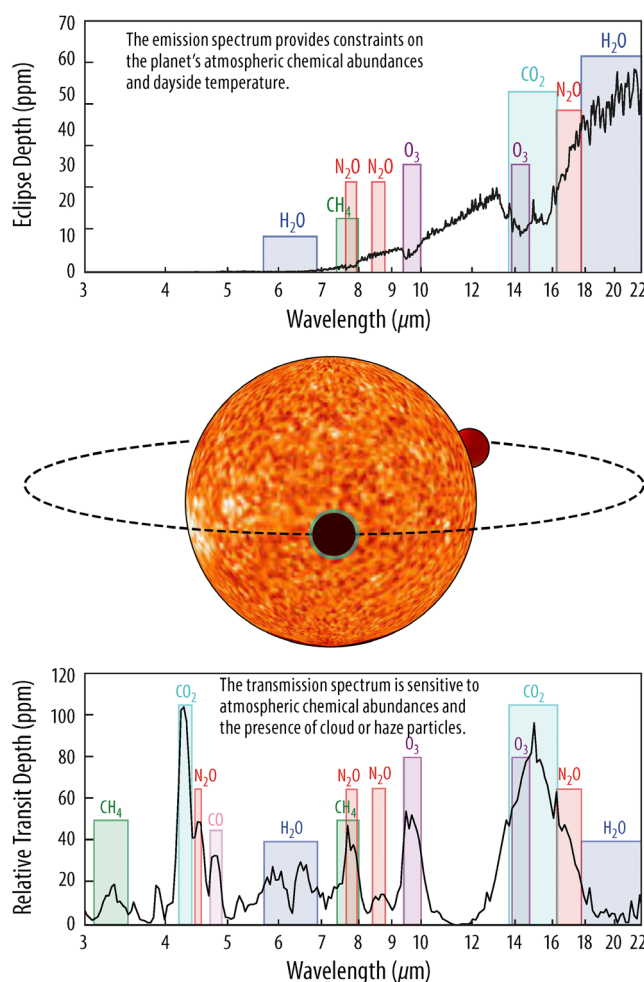


Fig. 8 The geometry and spectra for a typical transiting exoplanet. When a transiting planet passes in front of its host star, its apparent size changes as molecules absorb light at different wavelengths. When the planet passes behind the star, the planet's dayside thermal emission is measured, thus constraining a terrestrial planet's apparent surface temperature.

upon the legacy of Hubble and Spitzer – and soon JWST – with a midinfrared instrument specifically designed to characterize temperate, terrestrial exoplanets (Fig. 8). In its search for signs of life, Origins will employ a multitiered strategy, beginning with a sample of planets with well-determined masses and radii that are transiting nearby M dwarfs, the most abundant stars in the galaxy.²⁴ With its broad, simultaneous wavelength coverage and unprecedented stability, Origins will be uniquely capable of detecting signs of life.

The exoplanet science goal is specifically addressed by three questions described below, which correspond to the three tiers of exoplanet measurements in the search for life in M-dwarfs. The sample size is largest for the first tier experiment/question and becomes smaller for the second tier and third tier experiments as only the most promising-for-life exoplanet candidates are promoted in the investigation. These three measurements involve transit spectroscopy (Fig. 8) and specify both instrument and observatory requirements in the STM.

4.1 What Fraction of Terrestrial K- and M-Dwarf Planets Have Tenuous, Clear, or Cloudy Atmospheres?

In the first tier of its exoplanet survey, Origins will obtain transmission spectra over 2.8 to 20 μm for temperate, terrestrial planets spanning a broad range of planet sizes, equilibrium temperatures, and orbital distances, to distinguish between tenuous, clear, and cloudy atmospheres.

An atmosphere that is large and uninhibited by clouds at these wavelengths will exhibit large spectral features such as CO₂ in absorption. Because CO₂ absorption features are so strong, this tier can include terrestrial planets orbiting stars from late-M to late-K, giving Origins a broader perspective in the search for life than JWST.

4.2 *What Fraction of Terrestrial M-Dwarf Planets Is Temperate?*

For a subset of planets with the clearest atmospheres, Origins will measure their thermal emission to determine the temperature structure of their atmospheres. This is critical to assessing climate because it yields an understanding of how incoming stellar and outgoing thermal radiation dictate the heating and cooling of the atmosphere. Moreover, with this information the temperature at the surface of the planet can be estimated. Thus, Origins can then determine whether the planet could support liquid water near the surface.

4.3 *What Types of Temperate, Terrestrial M-Dwarf Planets Support Life?*

Origins will be the first observatory with the necessary spectroscopic precision to not only measure habitability indicators (H₂O, CO₂) but also crucial biosignatures (O₃ coupled with N₂O or CH₄), which are definitive fingerprints of life on habitable-zone planets. To address this third and most interesting question, Origins will obtain additional transit observations for the highest-ranked targets to search for and detect biosignatures with high confidence. The wavelength range afforded by Origins will provide access to multiple spectral lines for each molecular species. This will increase the detection significances and prevent potential degeneracies due to overlapping features, averting false positives. This framework robustly detects a variety of potentially habitable planet atmospheres, including those similar to the life-bearing Archaean Earth.

5 Origins Science Traceability Matrix

The Origins team took a holistic approach to the observatory by understanding not only the specific instrument and telescope needed to make a measurement but also how the observatory works to make the observation effectively and efficiently. Three instruments are specified to achieve the science goals of Origins: Origins Survey Spectrometer (OSS),¹³ Far-infrared Imager Polarimeter (FIP),²⁵ and Mid-Infrared Spectrometer Camera Transit channel (MISC-T).²⁶ Executing an observation requires understanding the choreography needed for the observatory¹ and instruments to work together to make a measurement. Analysis of conceptual observations with specific operational modes has been conducted to identify key Mission Requirements, such as telescope diameter, attitude control requirements, and efficiency requirements.

The three Origins science themes and their science objectives are captured in the mission's STM (Fig. 1). The STM's six columns show the flow down from NASA science goals (column 1), to the Origins science theme question (column 2), to the prioritized science objectives (column 3), to science requirements (column 4), to the instrument requirements (column 5), and mission requirements (column 6). The STM rows are the three science themes. Science requirements (column 4) have two subcolumns: the science observable and its corresponding measurement requirement. The four instrument requirement (column 5) subcolumns show the parameter, technical requirement needed to achieve the science goal, the instrument, and the current best estimate (CBE) performance of that instrument based on the study. The science goals are traced from left to right (columns 1 to 5). The mission requirements column (6) presents overarching mission capabilities needed to support a science theme, such as telescope collecting area and observatory pointing stability, as these parameters also stem from the science measurement requirements.

To illustrate the requirements flow, let us follow the first science goal, column 2, “How do galaxies form stars, build up metals, and grow their central SMBHs from reionization to today?” This science goal is achieved with three science objectives noted in column 3. The first objective is “measure the redshifts, star formation rates (SFR), and black hole accretion rates in main-sequence galaxies since the epoch of reionization down to an SFR of 1 M yr⁻¹ at cosmic noon

and 10 M yr^{-1} at $z \sim 5$, performing the first unbiased survey of the coevolution of stars and SMBHs over cosmic time.” To meet this objective, there are science requirements (column 4). The science observable (left subcolumn of column 4) is “A catalog of 10^6 galaxies with star-formation rates and black hole accretion rates measured using mid and far-IR emission lines.” This science observable gives rise to a measurement requirement (right subcolumn of column 4) for “moderate ($R \geq 100$) spectral resolution spectral mapping survey spanning 0.5 deg^2 and 20 deg^2 to deep and shallow depths, respectively.” The instrument requirements (column 5) specify the technical requirement for each instrument parameter needed to meet the measurement requirement. For example, the parameter, wavelength range, has a technical requirement of 25 to $500 \mu\text{m}$ for the OSS-grating mode of the OSS instrument. The concept OSS design has a CBE performance of 25 to $588 \mu\text{m}$ for the wavelength range. The mission requirement (column 6) of telescope diameter is $>5.0 \text{ m}$ if the extragalactic objectives# 1 to 3 are to be completed in a 4000-h observing campaign. However, the mission requirement of telescope diameter is $>3 \text{ m}$ to resolve source confusion expected in spectral mapping surveys.

Several Origins programs (e.g., science objectives 1 and 2 for the extragalactic goal) require large-area sky surveys, with the consequence that Origins needs to accomplish large-area surveys efficiently. To support such surveys, the mission required an observatory survey mode that supports 60 arcsecond per second motion while observing. The optimal performance of far-infrared direct detectors is such that rapid motion of a source over the detectors is required, which necessitates on-sky scanning or motion of a field steering mirror. The instrument and observatory need stability to fulfill the mid-infrared spectroscopy of exoplanet goals. Science targets are located all over the sky, which means the field of regard over the year must cover the entire sky. Origins’ requirement of $>80\%$ observing efficiency guides attitude control system development and operational scenarios outlined in the science cases.

The science requirements specified in the STM set the minimum necessary to achieve the science goal. However, the Origins design is roughly 25% more capable than required by these science requirements (e.g., Fig. 9), leading to what is denoted as “science margin.”

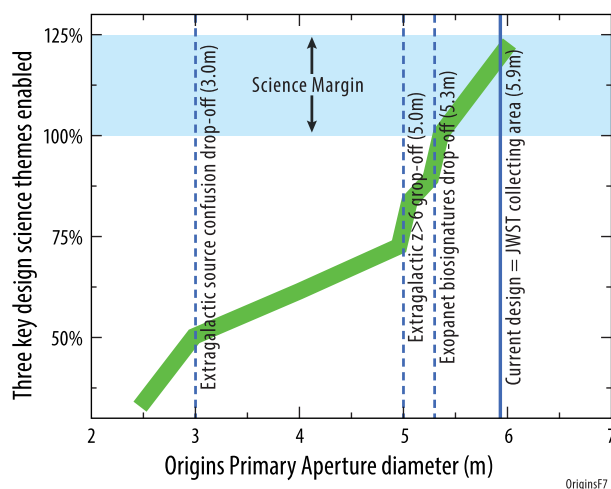


Fig. 9 Origins’ key science program requires a cold telescope with a primary aperture diameter of 5.3 m. This requirement comes primarily from the exoplanet science case to detect biosignatures in a 5-year mission, given that transit durations are fixed and sensitivity cannot be recovered with a longer single-epoch integration, unlike most other proposed Origins observations. The extragalactic study places an aperture size requirement of $>5 \text{ m}$, based on the need to detect a statistically significant sample of galaxies at $z > 6$, to study the formation mechanisms and physical properties of dust and metals during reionization. The minimum primary aperture diameter is 3 m to enable an effective extragalactic and Galactic science program, where source confusion does not compromise the telescope’s ability to conduct spectroscopic studies of galaxies at $z = 2$ to 3 and the sensitivity is not too poor to study water and gas in protoplanetary disks at the distances of Orion.

The margin can be interpreted in two ways: margin captures the uncertainty in the model predictions or the margin implies that the scientific objectives can be reached with lower integration times than predicted in calculations for the report.

The baseline mission provides a good starting point upon Origins selection, with the flexibility to explore alternatives during an engineering phase A study.¹ For example, Fig. 9 shows the fraction of each science theme that can be accomplished compared with the telescope diameter (collecting area). The baseline mission has a JWST collecting area (5.9-m diameter) that fits without deployments in the large launch vehicles under development. This size provides an estimated 25% margin for Origins' science driver cases.

6 Origins: Transformative Discovery Space

Origins is designed for discovery. The three science goals that drive Origins' design can be achieved in ~ 2 years based on our observational program scenario assessments. Thus, there will be significant time to address other science topics. Indeed, Origins is a true community observatory, and its science program will be driven by science proposals selected through the usual peer-review process, as used for existing large NASA observatories.

The Origins-enabled scientific advances described above are extensions of known science questions. However, history has shown that order-of-magnitude leaps in sensitivity lead to discoveries of unanticipated phenomena. For example, the sensitivity of IRAS over balloon and airborne infrared telescopes led to the discovery of debris disks, protostars embedded within dark globules, Galactic infrared cirrus, and infrared-bright galaxies, none of which were expected at the time of launch. Likewise, no study anticipated that Spitzer would determine the stellar masses of $z > 6$ galaxies and characterize the TRAPPIST-1 multiexoplanet system, the coldest known brown dwarfs, measure winds transporting energy in exoplanet atmospheres, and detect dust around white dwarfs produced by shredded asteroids.

Origins' sensitivity exceeds that of its predecessor missions by a factor of 1000.¹ Jumps of this magnitude are very rare in astronomy and have always revolutionized our understanding of the Universe in unforeseen ways. Moreover, the entire era of exoplanetary science has shown that Nature's imagination trumps our own, and Origins MISC-T's broad wavelength coverage and precise measurements are guaranteed to give us views into the new and unexpected. Thus, we anticipate a series of transformative discoveries by Origins that are impossible to imagine today.

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